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EFFECT OF MODE _SL_ SECTION ON COMBUSTOR PERFORMANCE AND STABILITY USING ROCCID

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Abstract

The ROCket Combustor Interactive Design (ROCCID) methodology is an interactive computer program that combines previously developed combustion analysis models to calculate the combustion performance and stability of liquid rocket engines. Test data from a 213 kN (48,000 lbf) Liquid Oxygen (LOX)/RP-1 combustor with a O-F-O (oxidizer-fuel-oxidizer) triplet injector were used to characterize the predictive capabilities of the ROCCID analysis models for this injector/propellant configuration. Thirteen combustion performance and stability models have been incorporated into ROCCID, and ten of them, which have options for triplet injectors, were examined in this study. Calculations using different combinations of analysis models, with little or no anchoring, were carried out on a test matrix of operating conditions matching those of the test program. Results of the computer analyses were compared to test data, and the ability of the model combinations to correctly predict combustion stability or instability was determined. For the best model combination(s), sensitivity of the calculations to fuel drop size and mixing efficiency was examined. Error in the stability calculations due to uncertainty in the pressure interaction index (N) was examined. The recommended model combinations for this O-F-O triplet LOX/RP-1 configuration are proposed.

Introduction

Until now there has been no industry standard methodology to aid in the design and analysis of combustion stable, high performance rocket engine combustors. The problem of evaluating the effect of changing design and operating parameters on combustion performance and stability is complex due to the number of physical mechanisms that need to be modeled.

Analytical models of combustion instability have been formulated to solve specific parts of the problem, but their application within the analysis procedure has varied with the different design methodologies used by engineers. As a result, engine design and analysis was a time consuming process, results were uncertain, and no base was available for comparing engines designed using different analytical models. In addition, many detailed models have been developed and a convenient method was needed to compare these models.

Producing a standardized methodology for performing engine design and analysis was addressed through development of the ROCket Combustor Interactive Design (ROCCID) methodology code. Existing performance and combustion stability models were evaluated[1] and assembled into an efficient, user friendly design and analysis code. An interactive front end guides the user through all stages of input setup and program execution. Linked together and controlled by computer logic, the models can interact and exchange information accurately and efficiently. With the procedure for engine analysis defined in the computer program, a standard methodology now exists for comparing engine designs developed using different models as well as comparing the capabilities of the performance and stability models. Currently no guidelines exist for selecting which models should be used for analyzing specific engine injector/propellant combinations, so the ROCCID code allows an interactive comparison of the models to evaluate various sensitivities.

The analysis models that are incorporated into ROCCID, model mechanisms that influence pressure waves which can oscillate inside the combustion chamber. One method to represent these mechanisms is the Response Factor Approach[2], which considers the separate processes

that influence the growth or decay of the pressure waves. The principle behind the Response Factor Approach states that in a system where several mechanisms are releasing heat or mass at once, wave growth is determined by the net in-phase or out-of-phase heat or mass addition. The wave will grow if heat or mass is added in-phase with the pressure, and the wave will decay if it is added out-of-phase. Analysis models have been developed which characterize the mechanisms that influence wave growth. Five categories of these analysis models, listed in Table I, have been incorporated into ROCCID: Chamber Acoustics, Combustion Response, Injector Admittance, Propellant Drop Size, and Sensitive Time Lag. An example of the nomenclature for describing a model combination in this study is also given. The models that are available in ROCCID are listed under each category, and are described in Table II. Within these models is the capability for modeling five different injector elements (triplet, like doublet, showerhead, shear coaxial, and swirl coaxial) and five propellant combinations (LOX/RP-1, LOX/H$_2$, LOX/CH$_4$, LOX/Propane and N$_2$O$_4$/Hydrazine propellants).

An experimental program[1] was undertaken to provide some data for the validation of the ROCCID methodology code. The ROCCID validation test engine was designed to produce a thrust of 213 kN (48,000 lbf) using Liquid Oxygen (LOX)/RP-1 propellants. The injector consisted of 105 O-F-O (oxidizer-fuel-oxidizer) triplet elements with 2.27 mm (0.090 in.) diameter fuel and oxidizer orifices impinging at 35° angles. The injector pattern was designed with the ROCCID methodology to produce wide operating regions of predicted combustion instability when tested without acoustic cavities, and regions of both stable and unstable operation when an acoustic cavity was present.

Since different models use different assumptions and methods in their calculations, stability predictions will vary with the different model combinations chosen for the analysis procedure. The purpose of this study was to compare, using little or no anchoring, the predictive capabilities of the different analysis models for the O-F-O triplet, LOX/RP-1 engine configuration. The effect on stability predictions which results from using different analysis models was examined to determine the characteristics of both individual models and groups of models. Performance and stability predictions made using different combinations of the models were compared to test data obtained from the validation engine. The percent of test points where combustion stability was correctly predicted was examined for each combination of models. Those combinations which predicted a high number of test points correctly were further examined, and the model combinations found to make the best predictions for this injector/propellant combination were selected as the recommended models to be used. The sensitivity of the performance and stability predictions to uncertainties in the mixing efficiency model, propellant drop size model, and pressure interaction index value were also examined.

Experimental Data

The ROCCID validation test program provided performance and stability data covering a wide range of operating conditions. A total of 27 test points were obtained, but 6 were determined to have short run times and were not examined in this

TABLE I. ANALYSIS MODELS AVAILABLE WITHIN ROCCID

Chamber Acoustics	Combustion Response	Injector Admittance	Drop Size Correlation	Sensitive Time Lag (τ) Correlation
H - HIFI D - DIST3D F - FDORC	C - CRP N - N-τ	I - INJ L - LEINJ	A - AEROJET P - PRIEM D - DROPMIX U - UTRC	A - AEROJET 20% S - SMITH-REARDON

Example: H N I D A

└─── Aerojet 20% τ Correlation
└─── Dropmix Drop Size Correlation
└─── INJ Injector Admittance Model
└─── N-τ Combustion Response Model
└─── HIFI Chamber Acoustic Model

2

study. Figure 1 shows the test points used for comparison in this study. The nominal operating point for this engine was at a chamber pressure of 8.6 x 10^6 N/m² (1250 psia) and a mixture ratio of 2.8. For the test points examined, the chamber

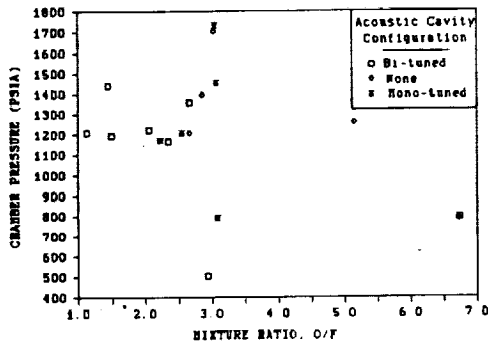Figure 1. Experimental Data

pressure of the engine varied from 3.5 x 10^6 N/m² (505 psia) to 12 x 10^6 N/m² (1735 psia). Mixture ratio ranged from a low of 1.13 to a high of 6.74.

Three different acoustic cavity configurations were tested with this engine. The first cavity configuration was a bi-tuned 1T/2T acoustic cavity ring, which was designed to provide test data in the most combustion stable engine configuration. The second configuration contained no acoustic cavity which was designed to provide baseline data on chamber sound speed and a direct assessment of the benefit of the bi-tuned 1T/2T cavity. The third cavity configuration was a mono-tune 1T acoustic cavity that has greater open area than the bi-tuned 1T/2T cavity. In this study, test points examined with the bi-tuned acoustic cavity

Table II. Combustion Performance and Stability Models Incorporated Into ROCCID

Model/ Correlation	Developed By Developed For	Approach	Applicable Hardware, Operating Conditions	Features
HIFI	Aerojet Phillips Laboratory	Linear Perturbation Technique With Mean and Fluctuating Components For Dependent Gas Dynamic Variables	Acoustic Resonators	Mechanistic, Burning Rate and Injection Coupled, Extensive Application History
DIST3D	Colorado State Phillips Laboratory	Calculates Baffle Damping Using a Turbulent Boundary Layer Model for Viscous Dissipation	Baffle Height and Blade Distribution Acoustic Resonators as Secondary Damping	Distributed Combustion, Mechanistic, Radial Baffles Only
FDORC	Colorado State Phillips Laboratory	Piecewise Distributed Combustion W/Arbitrarily Located Resonators	1/4 Wave Tube and Helmholtz Resonators and Liners	Distributed Combustion, Resonator Location, Mechanistic
CRP	Aerojet Phillips Laboratory	Uses Agosta-Hammer Non-Linear Vaporization Response Model	All for Which a Representative Drop Size Exists	Mechanistic, but Can Require Long Run Times
N-TAU	Smith-Reardon JANNAF	Correlation of Empirical N/τ Using a Sensitive Time Lag Model	Doublets, Triplets, Coaxial	Simple Historical Data Base, Non-Mechanistic
INJ	Aerojet NASA-LeRC	Lumped Parameter Anal. with Spacially Varying Acoustic Wave in the Chamber	All with Definable Total Timelag	Computes Injector Response Based on Element Timelag,
LEINJ	NASA-LeRC In-House	Modification of Feiler and Heidmann Feed System Coupled Instability Model to Include Manifold Acoustic Effects	Concentric Tube Elements	Include Flow Response Due to Manifold Acoustics if Important
AEROJET	Aerojet NASA-LeRC NASA MSFC	Potential Flow/Boundary Layer Breakup Calculation	Doublet, Triplet, Shear Coaxial, Swirl Coaxial	Mechanistic, Simple Off-Design Capability Total Time Lags Calculated
DROPMIX	WJSA Phillips Laboratory	Empirical Drop Size Correlations	Doublet, Triplet, Shear Coaxial	Improved Correlations Over SDER
PRIEM	NASA-LeRC In-House	Derived Empirically From LOX/HEPTANE Tests	Showerhead, Doublet, Triplet	Propellant Properties Effects Included, Historical Data Base, Limited Off-Design Capability
AEROJET 20%	AeroJet Phillips Laboratory	Use Observed Damp or Growth Rates to Infer Combustion Response	All Injectors for Which Empirical Growth or Damp Rates Exist	Required Experimental Data Base but Is a Means for Anchoring Stability Model
SMITH-REARDON	Reardon-Smith JANNAF	Correlation of Empirical N/τ Using a Sensitive Time Lag Model	Doublets, Triplets, Coaxial	Simple Historical Data Base, Non-Mechanistic

3

are referred to as 'Block I' data. Test points examined with no acoustic cavity are referred to as 'Block II' data, and test points examined with the mono-tuned acoustic cavity are referred to as 'Block III' data.

In addition, a post test cold flow injector experiment was developed for this study to examine O-F-O triplet injector spray fan formation and interaction as spacing between elements is reduced. Two cold flow injector faces were designed, each containing two O-F-O triplet elements matching those in the experimental engine. Spacing between the elements was reduced from 25.8 mm (1.016 in) to 9.14 mm (0.360 in). The injector sprayed into a non-confined area at atmospheric pressure. Flowrates for the experiment were set to obtain a momentum ratio of 3, approximately matching the momentum ratio of the LOX/RP-1 propellants.

Results and Discussion

Chamber Acoustics and Combustion Response

To characterize the predictive capabilities

of the different analysis models for the O-F-O triplet LOX/RP-1 configuration, performance and stability analyses were performed using different combinations of the models presented in Table I. All models in Table I can be used to analyze triplet O-F-O injectors except the LEINJ injector admittance model and UTRC drop size correlation, which were designed for coaxial elements. The FDORC chamber acoustics model was not examined in this study. For each analysis, ROCCID required that one model be selected from each column in Table I. Combinations which contain the CRP combustion response model, however, do not require a sensitive time lag parameter TAU (τ) correlation because the CRP model calculates its own τ parameter. Combining the remaining models resulted in a total of 18 different combinations. Each model combination was evaluated at the 21 different operating conditions of the experimental program shown in Fig. 1.

Results from the stability analysis are presented in Table III. The number of test points where stability was correctly and incorrectly

TABLE III. MODEL COMBINATION STUDY - STABILITY RESULTS

Model Combination	Block I Configuration Bi-tuned Acoustic Cavity		Block II Configuration No Acoustic Cavity		Block III Configuration Mono-tuned Acoustic Cavity		Percent of Correctly Predicted Test Points
	Correctly Predicted	Incorrectly Predicted	Correctly Predicted	Incorrectly Predicted	Correctly Predicted	Incorrectly Predicted	
HNIDA	6	3	5	1	4	2	72
HNIPA	6	3	4	2	5	1	72
DNIAA	5	4	4	2	5	1	67
DNIPA*	6	3	2	3	5	1	65
HNIAA	4	5	4	2	5	1	62
DNIDA	6	3	3	3	4	2	62
DNIDS	6	3	3	3	2	4	52
DCIP*	6	3	2	3	1	5	45
DCIA	5	4	2	4	2	4	43
DCID	5	4	2	4	2	4	43
HNIDS	7	2	2	4	0	6	43
HNIPS	7	2	2	4	0	6	43
DNIPS*	5	4	2	3	1	5	40
HNIAS	6	3	2	4	0	6	38
DNIAS	4	5	1	5	2	4	33
HCIP	4	5	1	5	1	5	29
HCID	4	5	1	5	0	6	24
HCIA	4	5	0	6	1	5	24

* One case did not converge to a solution.

predicted are broken down into three categories, corresponding to the acoustic cavity configuration. The percent of correct 1T mode stability predictions for each model combination is calculated in the last column. The models were ranked according to the percent of correct 1T stability predictions. Several trends in 1T stability predictions are apparent due to the selection of different models used in the ROCCID analysis procedure.

Stability predictions appear to be very sensitive to the sensitive time lag (τ) correlation selected. Comparing the percent of correct stability predictions made with each of the time lag correlations, combinations that used the Aerojet 20% τ correlation predicted a higher percent of correct cases than combinations using the Smith-Reardon correlation. Compared to the Aerojet 20% τ correlation, the Smith-Reardon correlation predicted a longer vaporization time lag.

Stability predictions also appear to be sensitive to the combustion response model and sensitive time lag selected. Examining the percent of correctly predicted cases, model combinations that incorporated the N-τ combustion response and Aerojet 20% τ correlation (-NI-A) predicted better than model combinations that used the N-τ and Smith-Reardon models (-NI-S) or used the CRP combustion response model (-C--). Combinations that included the N-τ combustion response and the Aerojet 20% τ correlation (-NI-A) predicted 62% of the test points correctly. Combinations that include the CRP combustion response model correctly predicted engine stability in less than 50% of the cases examined. A possible explanation for CRP's reduced performance is that the model characteristically calculates a short vaporization time lag. Since the LOX/RP-1 (liquid-liquid) triplet combination produces longer vaporization time lags, CRP may be more suitable for injector/propellant combinations such as a LOX/H$_2$

(liquid-gas) coaxial combination which produce a shorter time lag.

To select the best predictive model combinations, the conservative nature of model combinations when they predict incorrectly was examined. A model combination is considered to be conservative if it predicts a test to be unstable, when the test was observed to be stable. The six model combinations which incorporate the N-τ combustion response model and Aerojet 20% τ correlation (-NI-A) were the top ranked models based on correct stability predictions. The conservative nature of the top 6 model combinations is shown in Table IV by examining those test points which were incorrectly predicted. When the HIFI chamber acoustics model was used (HNI-A), the majority of incorrectly predicted cases were predicted unstable when the test was measured stable (a safe, conservative prediction). When the DIST3D chamber acoustics model was used (DNI-A), the majority of incorrectly predicted cases were predicted stable when the test was measured unstable. The HIFI chamber acoustics model was selected over the DIST3D model since HIFI would give the design engineer the greatest confidence that predicted stable tests would physically be stable. DIST3D calculates a distributed combustion response from the concentrated (lumped) τ parameter obtained from the N-τ model. This approximation may adversely affect the stability predictions and cause the non-conservative predictions.

The top ranked model combinations found for this engine configuration contain the HIFI chamber acoustics model, N-τ combustion response model, INJ injector admittance model, Dropmix or Priem drop size correlation, and Aerojet 20% τ correlation (HNIDA and HNIPA). These model combinations had the highest ranking based on correct stability predictions, and made conservative

TABLE IV. INCORRECT ROCCID STABILITY PREDICTIONS

Model Combination	Test Points Measured Stable But Predicted Unstable (Conservative Prediction)	Test Points Measured Unstable But Predicted Stable (Non Conservative Prediction)
HNIDA	4	2
HNIPA	4	2
HNIAA	6	2
DNIAA	2	5
DNIPA	2	5
DNIDA	3	5

calculations when cases were incorrectly predicted. To reduce the number of cases to be examined, the model combination HNIDA was selected to be used in the remaining studies.

Propellant Drop Size

No strong correlation was found between the drop size model selected and either the number of correct predictions or the conservative nature of the calculations except at mixture ratios less than 2.0. The propellant drop size was found to have a pronounced effect on stability predictions for cases operating at mixture ratios less than 2.0. Three drop size correlations have been incorporated into ROCCID, and each correlation predicted different fuel and oxidizer drop sizes for a given test point. Aerojet, Priem, and Dropmix correlations are available for the triplet injector. As an example of the uncertainty in drop size, for one test point the Aerojet, Priem, and Dropmix models calculated an oxidizer drop radius of 51, 17, and 20 microns

respectively. For another test the Aerojet, Priem, and Dropmix models calculated a fuel drop radius of 180, 40, and 44 microns respectively. Table V shows the 1T stability predictions made by ROCCID when the fuel and oxidizer drop size calculated by Dropmix were scaled up and down. Examining the five cases with mixture ratios less than 2.0 (test points 7, 13, 15, 20, 23), a trend developed when the fuel drop size was scaled. Of the five cases, stability was correctly predicted in only one case at the nominal fuel drop size. Scaling the fuel drop size down by 50% resulted in predicting all five cases correctly. At mixture ratios less than 2.0, scaling the fuel drop size calculated by Dropmix down 50% improved the predictions of the (HNIDA) model combination to 90%.

Mixing Efficiency

Performance and stability analyses were performed for the 21 test points over a range of

TABLE V. DROP SIZE SENSITIVITY STUDY

Model Combination: HNIDA			Observed Stability	Correctly Predicted Combustion Stability/Instability				
Test Point	O/F	Pc (psi)		Nominal Dia	0.5*Ox Dia	1.5*Ox Dia	0.5*Fuel Dia	1.5*Fuel Dia
7	1.45	1441	Stable	N	Y	N	Y	N
9	2.94	505	Stable	Y	Y	Y	N	Y
13	1.13	1210	Stable	N	N	N	Y	N
14	2.67	1358	Unstable	Y	Y	Y	N	Y
15	1.93	968	Stable	N	N	N	Y	Y
17	6.74	792	Stable	Y	Y	Y	N	Y
18	2.35	1165	Unstable	Y	Y	Y	N	N
19	2.06	1220	Unstable	Y	Y	Y	N	Y
20	1.50	1193	Stable	Y	N	N	Y	N
21	2.67	1208	Unstable	Y	Y	N	N	N
23	1.25	1004	Stable	N	N	N	Y	Y
24	6.71	788	Stable	Y	Y	Y	N	Y
25	2.86	1397	Unstable	Y	Y	Y	N	Y
27	3.03	1706	Unstable	Y	Y	Y	N	Y
28	5.15	1260	Unstable	Y	N	Y	N	N
29	2.55	1208	Unstable	Y	N	Y	N	N
30	3.09	791	Unstable	N	N	N	Y	N
37	3.05	1735	Unstable	Y	Y	Y	N	Y
38	3.07	1456	Unstable	Y	Y	Y	N	Y
39	5.60	1213	Unstable	N	N	N	N	N
40	2.23	1172	Unstable	Y	Y	Y	N	N

mixing efficiencies to examine the effect on predictions. Based on results from a similar test program[3], a nominal mixing efficiency of 87% was used. Since the mixing model in ROCCID generally over-predicted mixing efficiency and over-predicted the performance, reduced mixing efficiencies of 84%, 76%, 70% and 66% were examined. The energy release efficiency (ERE) obtained from the test program was compared to the value calculated by ROCCID to measure the change in performance. The ERE value accounts for combustion efficiency limitations resulting from incomplete propellant vaporization and/or mixing and is described further in Ref. 1. To examine the effect on stability due to the different mixing efficiencies, ROCCID predictions of stable/unstable combustion were compared to the observed results of the test program.

Results of the performance analysis showed that the mixing efficiency had a strong influence on predicted engine performance and at low mixture ratios, there is a large uncertainty in the calculations. Figure 2 shows the ERE calculated for each test point over the range of mixing efficiencies.
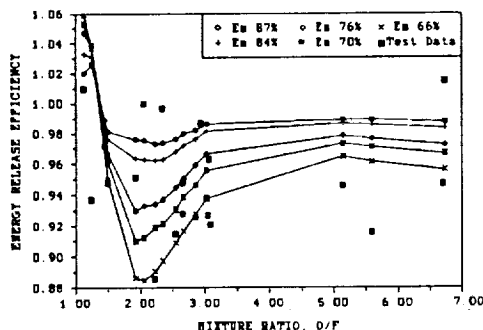
Figure 2. Engine Performance

The performance of this injector was much lower from that observed in Ref. 3. This lower performance was unexpected because this injector had smaller holes than that in Ref. 3, and the models generally predict greater performance for smaller holes. It was theorized during the test program that although the holes were smaller, the sheets created by the triplet injector interfered with each other because of their close proximity[4]. This theory was investigated using water flow tests of two triplet elements separated by different distances. Figure 3 shows the visualization of the water flow of the elements. Figure 3A shows two O-F-O triplet elements separated by 2.946 cm (1.160 in) corresponding to the distance in Ref. 3.

Figure 3B shows two O-F-O triplet elements separated by 0.914 cm (0.360 in) corresponding to the distance in this test program. It is evident in Fig. 3B that the element sheets formed by the impinging jets do not fully develop, and they interfere with each other at the impingement point rather than farther down stream as shown in Fig. 3A. This interference can cause unexpected drop size and mixing anomalies. None of the models account for inter-element distance. It is recommended that inter-element distance effects should be studied further to determine their importance and to incorporate them into the models.

As the mixing efficiency was reduced from its nominal value, the calculated ERE decreased for all test points except those at extremely low mixture ratios. For the two test points with the lowest mixture ratios (1.13 and 1.25), the ERE was calculated by ROCCID to be greater than 1.0. As the mixing efficiency was decreased from it's nominal value, the ERE calculated for these two test points increased. This anomaly appears to stem from Fig. 4, the theoretical ISP vs. mixture ratio plot calculated by ODE for ROCCID. ROCCID calculates the ERE by dividing a theoretical ISP (ISP_{THEO}) by a mass-weighted, multi-zone ISP ($ISP_{M.Z.}$). ISP_{THEO} is interpolated from Fig. 4 based on the injected mixture ratio. The $ISP_{M.Z.}$ is calculated within ROCCID using a multi-zone stream tube method described in Ref. 5. The $ISP_{M.Z.}$ is obtained from a low mixture ratio ISP and a high mixture ratio ISP relative to the injected mixture ratio. Both the low and the high mixture ratio ISP values are extrapolated from Fig. 4. When the injected mixture ratio occurs at the inflection point between mixture ratios of 0.9 and 1.4, the $ISP_{M.Z.}$ is interpolated to be higher than the ISP_{THEO} as shown in Fig. 4 for test #13. This
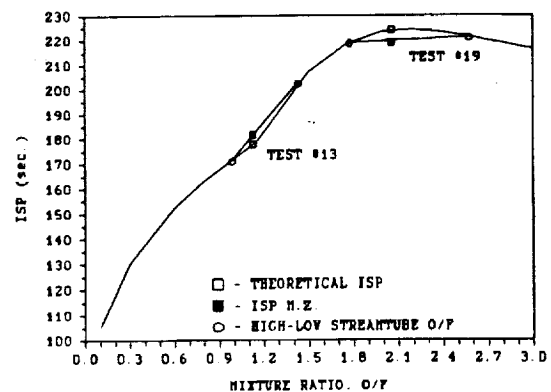

Figure 4. ODE Calculated Specific Impulse

7

Figure 3A. 2 O-F-O Triplet Elements (Spacing = 1.160 in)

Figure 3B. 2 O-F-O Triplet Elements (Spacing = 0.360 in)

results in a ERE value greater than 1.0. For test #19 which has a higher injected mixture ratio than test #13, Fig. 4 shows how the $ISP_{M.Z.}$ is interpolated to be less than the ISP_{THEO}. The inflection point in the performance curve for LOX/RP-1 is not present in the performance curve for LOX/H2. This anomaly must be considered when analyzing an engine but appears to be restricted to the case of LOX/RP-1 propellants.

Results from the stability analysis show that reducing the mixing efficiency improved the stable combustion characteristics by a small margin. Figure 5 shows the 1T stability results for the 21 test points using mixing efficiencies from 87% to
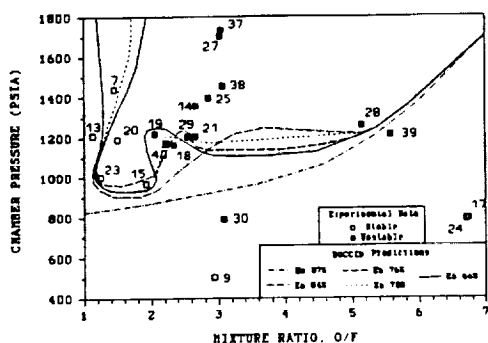
Figure 5. 1T Mode Stability Map

66%. Each line shows the 1T mode stability boundary predicted for the respective mixing efficiencies, with the stable region below the line and the unstable above. The open squares represent test points observed stable, and the solid squares represent test points observed unstable. The overall effect of reducing the mixing efficiency was to increase the stable operating region. Of the 21 test points, 7 showed change in the predictions as the mixing efficiency was reduced. The percent correctly predicted cases fluctuated by ±5% over the range of mixing efficiencies examined.

Effect Of The Pressure Interaction Index (N)

The pressure interaction index, which describes the combustion rate for small perturbations, affects the high frequency combustion response of the injector. The sensitivity of the stability predictions to the pressure interaction index (N) was examined for the three acoustic cavity configurations. Based on data from Ref. 6, the uncertainty in N was estimated to be ±26 percent for this O-F-O triplet, LOX/RP-1 configuration. A high frequency analysis was performed for each of the 21 test points using pressure interaction index values of: the calculated

N, +26% calculated N (1.26*N), and -26% calculated N (0.74*N). The calculated 1L, 1T and 2T instability boundaries were plotted on a Pc Vs. O/F graph to visualize how the stable/unstable regions change with N.

Figures 6, 7, and 8 present the stability boundaries predicted for the bi-tuned (Block I), no acoustic cavity (Block II), and mono-tuned (Block III) acoustic cavity configurations, respectively. Test points obtained with each cavity are noted on the graphs along with their observed stability (S: stable, U-1T: unstable 1T mode, U-2T: unstable 2T mode). For all cases, the 1L predictions are questionable, since ROCCID calculates a large region of unstable operation and no 1L instabilities were encountered during the test program. All three plots show that this engine is stable in the 1T and 2T modes below 5.5×10^6 N/m² (800 psia). They also show that higher values of N result in larger predicted regions of unstable combustion for the 1T and 2T modes.

Predicted instability boundaries for the bi-tuned chamber configuration (Block I) are presented in Fig. 6. Figure 6A shows the instability boundaries calculated for N-26%. The damping effect of the acoustic cavity was predicted by ROCCID because the 1T boundary is diverted around the nominal operating point, 8.6×10^2 N/m² (1250 psia) and O/F=2.8. As N is increased to its nominal value, Fig. 6B, the stable region at high Pc disappears and the lower boundary of the 1T instability expands down to lower chamber pressures and higher mixture ratios. With the increased N, ROCCID predicts the acoustic cavity to have a reduced damping effect shown by the larger unstable 1T and 2T regions. Figure 6C shows the predicted engine stability calculated with the pressure interaction index increased by 26%. All 3 plots show conservative stability predictions for Block I test points, as incorrectly predicted test points were predicted unstable but observed stable.

Predicted stability boundaries for the undamped chamber configuration (Block II) are presented in Fig. 7. Figure 7A presents the 1T and 2T mode instability boundaries predicted with a 26% reduced pressure interaction index. As N is increased to its nominal value (Fig. 7B) the 2T mode boundary extends down from 12×10^6 N/m² (1700 psia) to 9.0×10^6 N/m² (1300 psia). The 1T mode boundary has the most pronounced growth, extending down to 6.2×10^6 N/m² (900 psia) and a mixture ratio of 6.0. Figure 7C shows the instability boundaries calculated for N increased by
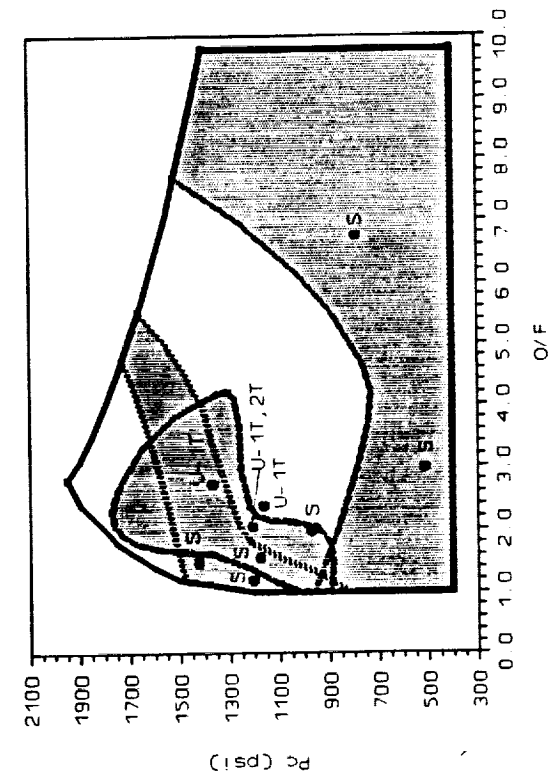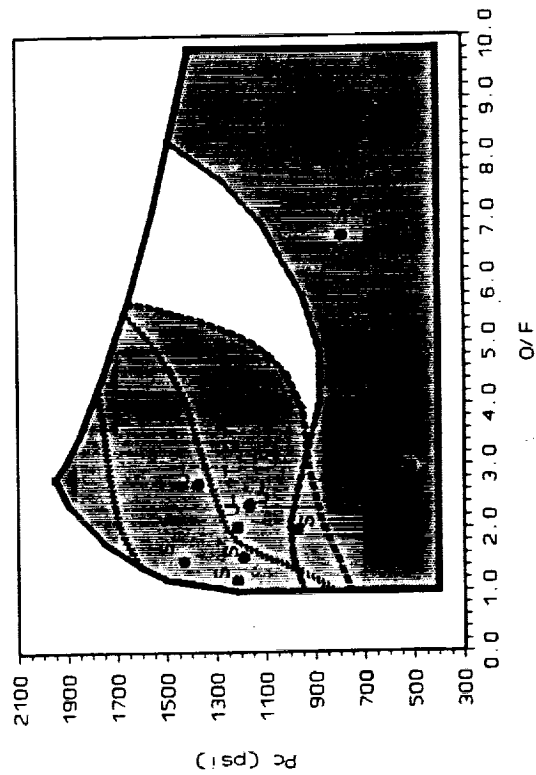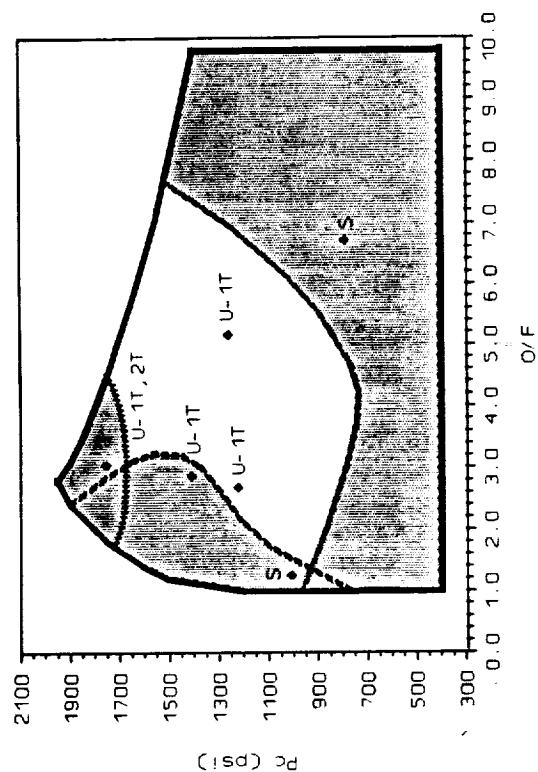
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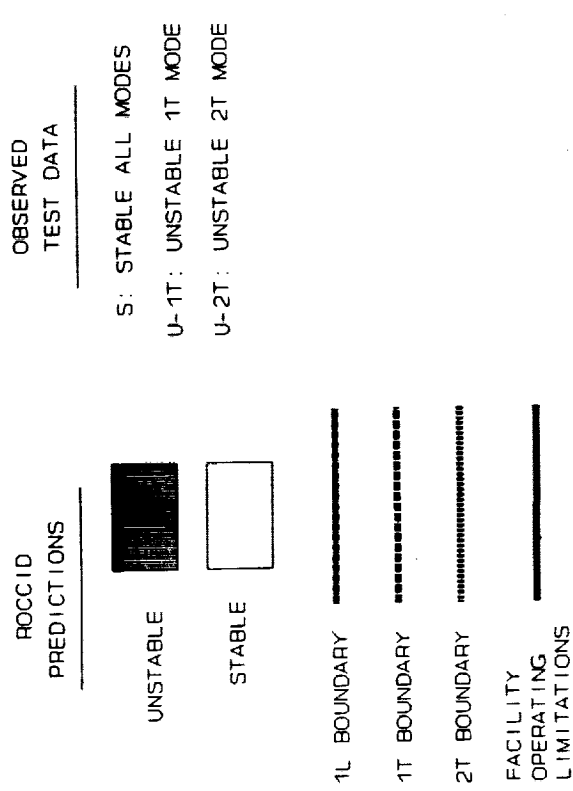
FIGURE 6. STABILITY MAPS, BI-TUNED 1T/2T ACOUSTIC CAVITY

10

FIGURE 7C. PRESSURE INTERACTION INDEX=(N+26%)
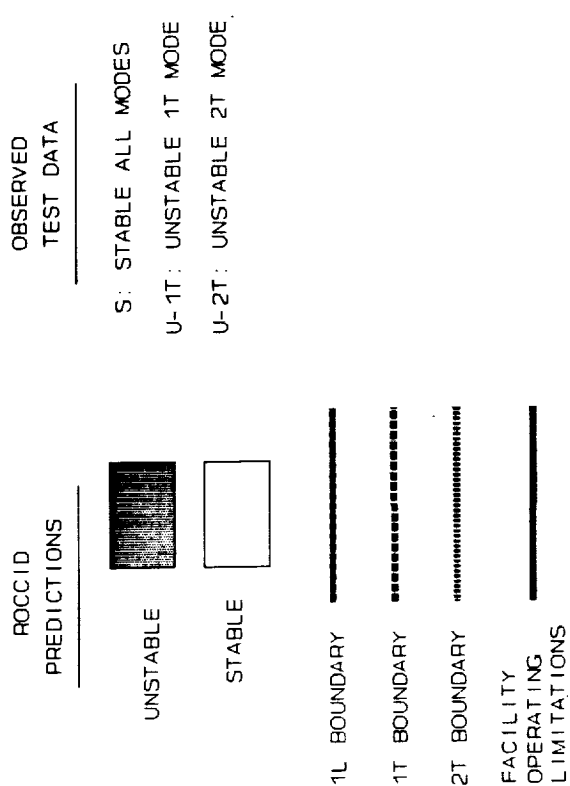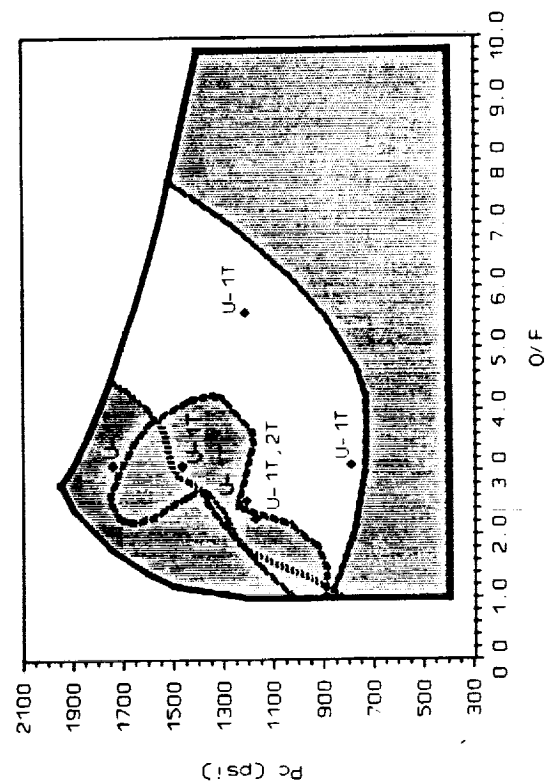
FIGURE 7A PRESSURE INTERACTION INDEX=(N-26%)
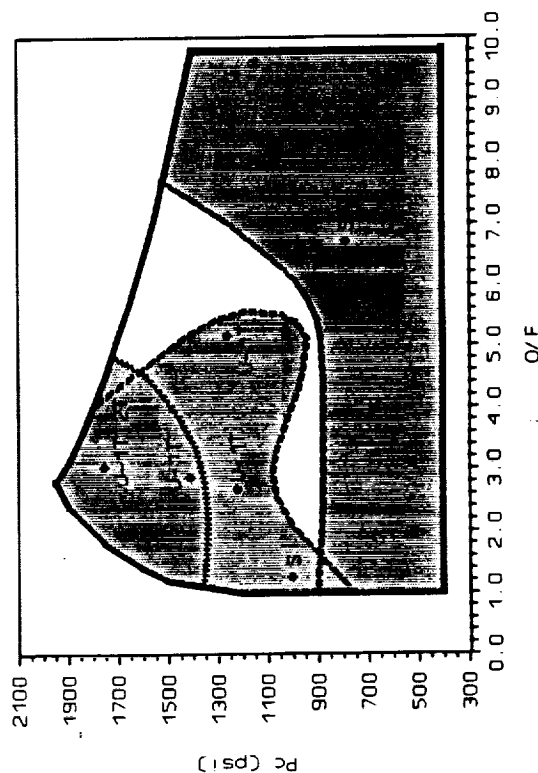
FIGURE 7B. PRESSURE INTERACTION INDEX=(N)

OBSERVED
TEST DATA

S: STABLE ALL MODES

U-1T: UNSTABLE 1T MODE

U-2T: UNSTABLE 2T MODE

ROCCID
PREDICTIONS

UNSTABLE

STABLE

1L BOUNDARY

1T BOUNDARY

2T BOUNDARY

FACILITY
OPERATING
LIMITATIONS

FIGURE 7. STABILITY MAPS, NO ACOUSTIC CAVITY

11

FIGURE 8A. PRESSURE INTERACTION INDEX=(N-26%)
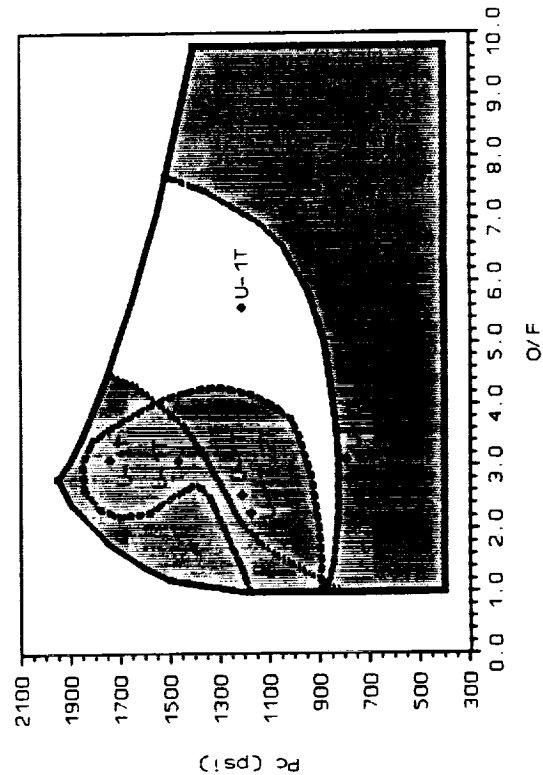
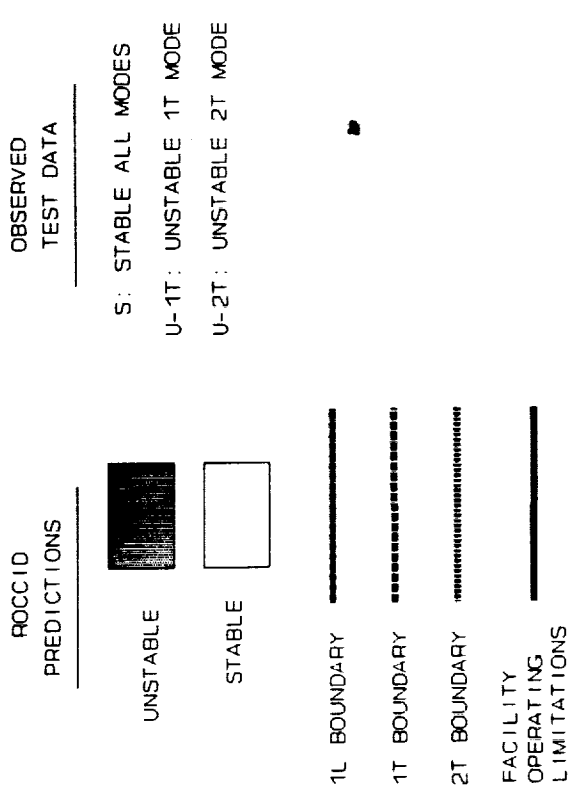FIGURE 8B. PRESSURE INTERACTION INDEX=(N)

FIGURE 8C. PRESSURE INTERACTION INDEX=(N+26%)

FIGURE 8. STABILITY MAPS, MONO-TUNED ACOUSTIC CAVITY

26%. For this case, only a small region of stable operation is predicted. Using pressure interaction index values of N and N+26% resulted in conservative stability predictions for Block II test points.

Predictions for the mono-tuned acoustic cavity are presented in Fig. 8. Figure 8A presents the instability boundaries calculated with N reduced 26%. Similar to Fig. 6A, the effect of the acoustic cavity is observed as the 1T boundary is diverted around the nominal operating point of 8.6 x 10⁶ N/m² (1250 psia) chamber pressure and 2.8 mixture ratio. With the absence of the 2T cavity in the Block III tests, the stable region in Fig. 6A at high pressures, Pc > 10 x 10⁷ N/m² (1500 psia), is now enveloped by the predicted 2T boundary. Examining predictions using the calculated N (Fig. 8B), the larger open area of the mono-tune cavity still has a stabilizing effect on the predicted 1T boundary near the nominal operating point. As N is increased to N+26% and the predictions become more conservative, Fig. 8C shows that the cavity is predicted to have a minimal damping effect. Only the plot for N+26% represents conservative stability predictions for the Block III test points.

Conclusions

Test data from a 213 kN (48,000 lbf) LOX/RP-1 engine with an O-F-O triplet injector were used to characterize the predictive capabilities of different analysis models within the ROCCID program. Analyses were performed with different performance and stability models to expose trends in calculated results. For model combinations that gave the best stability results, sensitivity of the stability predictions to propellant drop size, overall mixing efficiency and pressure interaction index was examined. Characteristics of the predictions highlighted by this analysis are:

1. For this engine configuration, model combinations which use the HIFI chamber acoustics model, N-τ combustion response model, INJ Injector admittance model, Dropmix or Priem drop size correlation, and the Aerojet 20% τ correlation (HNIDA and HNIPA) provide the best predictive capability and most conservative calculations. They are the recommended model combinations for analyzing an O-F-O triplet, LOX/RP-1 combustor.

2. Unanchored, stable/unstable operation was correctly predicted in 72% of the cases

examined.

3. Applying the results of this analysis and anchoring the fuel drop size for cases where MR < 2.0, stable/unstable operation was correctly predicted in 90% of the cases examined.

4. Due to uncertainties in the drop size predictions, uncertainties in the stability predictions were produced. This was particularly true for mixture ratios under 2.0.

5. The Combustion Response model (CRP) did not predict well for this injector/propellant combination, possibly due to its short calculated time lag.

6. Mixing efficiency did not have a large effect on stability predictions.

7. The mixing efficiency model in ROCCID over-predicts engine performance and should be examined for corrections.

Concluding Remarks

By combining the best performance and stability models into one program and giving them a standard base for comparison, ROCCID has made it possible to rigorously evaluate the models incorporated into the program. Until better models can be developed to accurately and consistently predict the critical parameters that affect engine performance and stability, predictions by the models in ROCCID will have a large error band. Improved diagnostic equipment will permit the acquisition of better data to improve and validate the models. More mechanistic models can be incorporated into ROCCID, which require fewer assumptions in their calculations. CFD generated empirical models for portions of the combustor can also be incorporated.

Predicting combustion stability in a rocket engine is not a trivial problem. Figures 6 through 8 show the great advantage of ROCCID. Graphs like these were difficult and time consuming to produce before ROCCID. Now it is relatively easy to determine a stable operating envelope for an engine design. ROCCID provides a standard methodology for evaluating the effects of design and operating parameters on engine performance and stability. In its present form, ROCCID can be used to improve the efficiency of the engine design

process. Low CPU requirements compared to more detailed numerical codes allow a large number of cases to be examined. This permits the engineer to focus in on a high performance, stable engine configuration. Advanced numerical methods used to fine tune the design can be applied to the small operating region defined by ROCCID.

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13. ABSTRACT (Maximum 200 words)

The ROCket Combustor Interactive Design (ROCCID) methodology is an interactive computer program that combines previously developed combustion analysis models to calculate the combustion performance and stability of liquid rocket engines. Test data from 213 kN (48,000 lbf) Liquid Oxygen (LOX)/RP-1 combustor with a O-F-O (oxidizer-fuel-oxidizer) triplet injector were used to characterize the predictive capabilities of the ROCCID analysis models for this injector/propellant configuration. Thirteen combustion performance and stability models have been incorporated into ROCCID, and ten of them, which have options for triplet injectors, were examined in this study. Calculations using different combinations of analysis models, with little or no anchoring, were carried out on a test matrix of operating conditions matching those of the test program. Results of the computer analyses were compared to test data, and the ability of the model combinations to correctly predict combustion stability or instability was determined. For the best model combination(s), sensitivity of the calculations to fuel drop size and mixing efficiency was examined. Error in the stability calculations due to uncertainty in the pressure interaction index (N) was examined. The recommended model combinations for this O-F-O triplet LOX/RP-1 configuration are proposed.

14. SUBJECT TERMS

Combustion stability; Combustion efficiency; Rocket engine design; Combustion chambers; Rocket thrust chambers

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